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Modelling of far-field pressure plumes for carbon dioxide sequestration

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Abstract

We apply both numerical modelling, by means of single-phase and two-phase models, and analytical calculation for estimation of far-field pressure buildup, considering a generic scenario of dipping aquifer and a site-specific scenario for the Scania site, southwest Sweden. We examine the effect of depth-dependent fluid and material properties as well as formation geometries on far-field pressure buildup. The use of simple analytical calculations, including the Theis equation and superposition based on the method of images, for the estimation of pressure buildup is evaluated. The results are also discussed in terms of comparison between the numerical simulations and simple analytical calculations.

Keywords: Geological storage; Pressure buildup; Numerical modeling; Analytical solution; Capacity

1. Introduction

Carbon dioxide (CO_2) sequestration in deep saline aquifers has been widely recognized as a promising technology for mitigation of atmospheric CO_2 concentration increase. Effective implementation of CO_2 sequestration involves injection of large volumes of CO_2 which causes pressure perturbation in the storage formations. The pore volume needed for storing CO_2 in the closed formations is accommodated by reduction in the volume of the formation fluid (through compression or displacement of the formation

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fluid) and enlargement of the pore space (though compression of the rock material) [1]. Geological storage of CO_2 is accompanied by pressure increase in the host formation and can result in large-scale brine migration that may have major secondary effects of concern on the near-surface (fresh water) aquifers. It is therefore needed to carefully examine the evolution and impact of the pressure plume and far-field brine migration caused by commercial scale CO_2 injection. In this article, we focus on the issue of pressure buildup at the far-field (i.e., regions of the formation far away from the CO_2 plume).

Pressure buildup associated with supercritical CO_2 injection has been studied by numerical simulations [e.g., 2-5] and analytical methods [e.g., 1, 6-8]. Site specific simulations have provided insights and predictions on pressure buildup for given aquifer conditions. Nicot [2] studied the pressure anomaly at the far-field for a tilted, wedge-shaped aquifer of the Texas Gulf Coast Basin, considering two injection scenarios (two injection rates of 1 and 5 million tonnes per year per well). The result shows that the water-level rise in the unconfined part of the injection formation is approximated 1 m at the end of injection period for the smaller rate scenarios but could reach 15 m for the larger injection rate. Zhou et al. [4] performed a basin-scale investigation for multiple-site CO_2 injection in the Mt. Simon aquifer in the Illinois Basin. They simulated CO_2 injection with a rate of 5Mt/year/well and a total number of 20 wells. The result shows that the simulated pressure buildup in the core injection area is about 35 bars and is not expected to affect the caprock geomechanical integrity. The study also shows that a pressure increase of 1 bar and 0.1 bar can be predicted for a distance of 150 km and 300 km away from the injection area, respectively. Some recent effort has been focused on simple analytical methods [e.g., 6, 7]. Zhou et al. [6] developed a simple analytical method for the quick assessment of the pressure buildup and storage capacity in closed and semi-closed reservoirs. Mathias et al. [7] presented an explicit approximate analytical solution for estimating pressure buildup due to injection of CO_2 into open or closed aquifers. This approximate analytical solution has also been extended to account for the effect of partial miscibility of CO_2 and brine [8].

Large-scale pressure buildup and far-field brine migration, and associated impacts on the environment, may become a limiting factor for the CO_2 storage capacity [3]. Birkholzer and Zhou [3] pointed out that these basin-scale hydrogeological impacts should be taken into account for the regional and global capacity estimation, which typically has been based on simple calculation of the fraction of the total reservoir pore space [9]. The potential impact of CO_2 sequestration on shallow groundwater resources has been recently reviewed in [10].

A number of factors affect the size of the propagating pressure plume and the magnitude of the pressure buildup. These factors include: (i) properties of the formation material and fluids; (ii) formation geometry and boundary conditions; and (iii) brine leakage through confining layers and fractures zones and faults. In this study, we examine the effect of depth-dependent fluid and material properties as well as formation geometries on far-field pressure buildup, by numerical simulations. We also evaluate the use of simple analytical calculations for the estimation of pressure buildup.

2. Methods

We apply both numerical modelling and analytical calculation for the estimation of far-field pressure buildup, considering a generic scenario of dipping aquifer and a site-specific scenario for the Scania site, southwest Sweden. We compare results from numerical modelling and analytical calculation in Section 4.

2.1. Numerical modelling using TOUGH2 with ECO2N

Numerical simulations are conducted using the multiphase flow simulator TOUGH2 [11] with the equation-of-state module ECO2N [12]. TOUGH2/ECO2N accounts for the complex thermodynamics of supercritical CO_2 injection and migration in saline aquifers. Injection and migration of CO_2 into brine formations present a two-phase flow problem. However, the CO_2-brine two-phase flow region is typically restricted within a few kilometres around the injection well, while the lateral extent of suitable aquifers for large-scale deployment of CO_2 storage usually needs to be several tens or a few hundreds kilometres. As will be shown in Section 4, we have numerically simulated CO_2 injection in an ideal (horizontal, confined, homogeneous, isotropic and infinite) aquifer and examine the pressure buildup outside of the two-phase flow zone at the different distances away from the injection well. It is confirmed that the two-phase flow region has negligible effect on the pressure buildup at distances far away, compared to the pressure buildup estimated by simple analytical solution for single-phase brine flow. This also supports the approach used in [2]. Thus, in order to reduce the computational time, we have considered only brine injection for the generic, dipping aquifer scenario and the site-specific scenario for the Scania site.

2.2. Analytical methods for calculation of pressure buildup

In the context of pressure buildup in the vicinity of the injection well, recent advances on semi-analytical solutions have been presented [1, 7-8]. For estimation of the far-field pressure buildup, the simplification of assuming single-phase flow may be made. In groundwater hydrology, analytical solutions have been developed to estimated hydraulic drawdown for a number of different conditions. One of the fundamental developments of the hydrological methodology is the Theis solution [13] which, written in terms of pressure buildup ΔP at radial distance r and time t for an ideal aquifer, is

$$\Delta P = P - P_0 = \frac{Q\mu_b}{4\pi kb}\int_u^{\infty}\frac{e^{-u}}{u}du \tag{1}$$

where

$$u = \frac{r^2 S\mu_b}{4tk\rho_b gb} \tag{2}$$

In eqs. (1-2), P is the vertically averaged pressure, P_0 is the initial pressure (vertically averaged), Q is the volumetric injection rate, k is the permeability of the reservoir, S is the storativity of the reservoir, b is the thickness of the reservoir, ρ_b is the density of the native brine, μ_b is the viscosity of the brine. The integral in eq. (1) is the exponential integral and maybe evaluated using a convergent series for $u < 2.5$.

Storage aquifer may have a caprock layer with permeability that is not sufficiently low to constrain brine leakage but functions as a capillary barrier for the non-wetting CO_2 phase. In this leaky-aquifer case, the assumption of impermeable confining layers for the Theis solution does not hold. Analytical solutions for this case have been developed by, e.g., Hantush and Jacob [14] and Neuman and Witherspoon [15], and have been recently applied by [5] for assessment of pressure response due to CO_2 storage.

Lateral extent of real-world reservoirs varies, but is never infinite. Reservoirs are created by complex geological processes that can lead to irregular geometries, such as pinchouts and boundaries formed by fault zones. For a reservoir bounded by cemented (impermeable) faults, the method of images [16] may be used for the analytical calculations. In this study, we will evaluate the use of simple analytical methods with imaginary injection wells for a potential storage site (see Section 4).

3. Modelling Scenarios

3.1. Scenario 1: a dipping aquifer with depth-dependent formation medium properties

A schematic for the geometry of the generic aquifer in this scenario is given in Fig. 1. The dipping aquifer considered has a slope of 0.0125 and a uniform thickness of 50 m. The porosity φ is assumed to be related to the depth Z in the domain as $\varphi = 0.00004 \times Z + 0.3$, which is loosely based on [5]. The permeability is then assumed to be linked to the porosity as $\log_{10}(k) = 15.58 \times \varphi - 16$, based on [17]. Temperature and salinity gradients are also considered. The injection well is placed in the middle of the aquifer (X = 160 km and Y = 100 km).

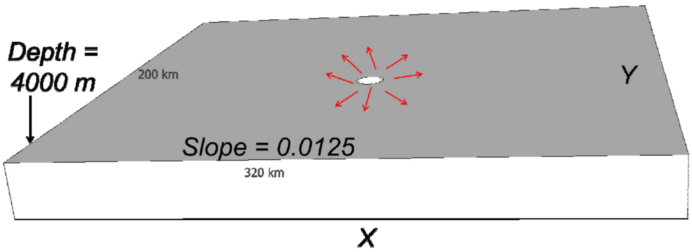

Fig. 1. Schematic of a dipping aquifer extending from a depth of 4000 m to the ground surface.

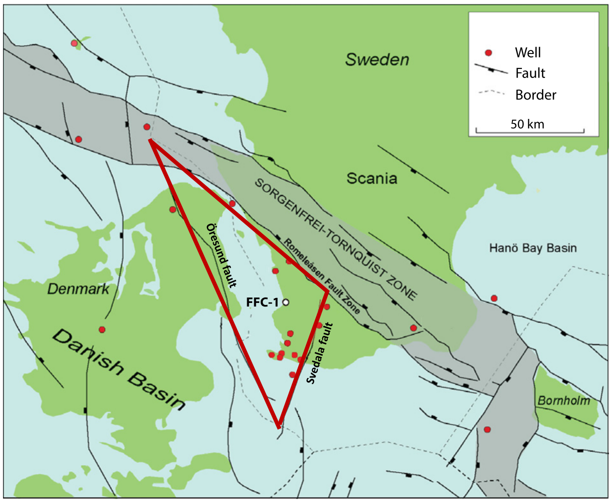

Fig. 2. Map of the Scania site. The red triangle shows the idealised boundaries of the considered reservoir imposed by three faults.

3.2. Scenario 2: the Scania site, southwest Sweden

The Scania site is located in the southwestern region of Sweden (Fig. 2). A number of deep boreholes have been drilled and these boreholes reveal existence of several sandstone layers which constitute potential candidates for geological storage of carbon dioxide [17]. These sandstone layers appear in the Lower Cretaceous and Upper Jurassic sequences. In this study, we consider a storage reservoir consisting of these layers within the depth interval between 1650 m and 1725 m. The reservoir is bounded by three faults (conceptualized into straight lines and shown in red lines in Fig. 2). The faults are considered sealed by fault gauge and plastic argillaceous layers overlying the fault escarpments and thus impose closed boundaries for the reservoir which becomes triangular-shaped in a planar view. In this case, we are primarily interested in the pressure build at the faults due to fluid injection (at the FFC-1 well), as over-pressurization may cause fault reactivation. We assume a uniform thickness for the reservoir and simplify the case to perform a two-dimensional (vertically integrated) numerical analysis. We simulate the pressure buildup with an injection rate of 1.5 Mtonne/year. Based on the available site data, we assume a homogeneous permeability of 1.0×10^{-13} m^2 and a porosity of 0.15. The pore compressibility is taken as 3.71×10^{-10} Pa^{-1}. A recent study on the effect of heterogeneity on fluid migration and upscaling based on the Scania site is presented in [18]. A more detailed description of the site can be found in [17, 19].

4. Results

4.1. CO_2 injection into an ideal saline aquifer

We have simulated CO_2 injection in an ideal, disk-shaped aquifer with a rate of 1 Mtonne/year and a time span of 50 years. The aquifer has a lateral extent of 250 km and is discretized into a 2-D radial mesh. The radius (250 km) is sufficiently large so that the boundary does not have any impact on the two-phase flow process and the pressure buildup in the system, i.e., the aquifer is acting as an infinite one. The two-phase flow parameters for the formation material are taken from [4] for the Mt. Simon sandstone. It can be seen from Fig. 3 that the analytical Theis solution matches the simulations for the pressure increase at different distances from the injection well. This may be expected as these distances are much larger than the two-phase flow region (within a radius of 2.5 km at 50 years). The result also indicates that it is adequate to only consider single-phase brine flow for estimating far-field pressure buildup.

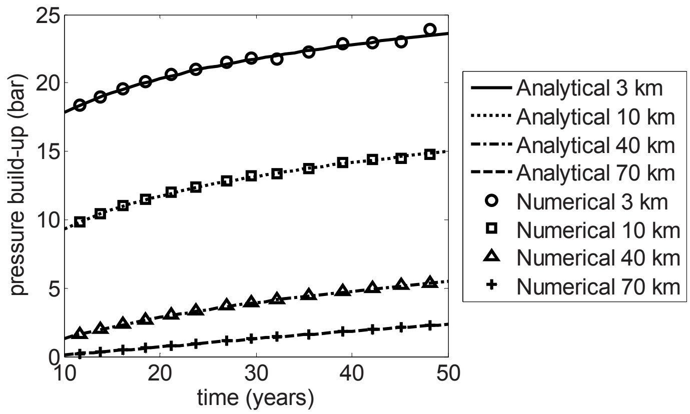

Fig. 3. Comparison of pressure buildup from numerical simulations of CO_2 injection and the Theis solution for an ideal aquifer.

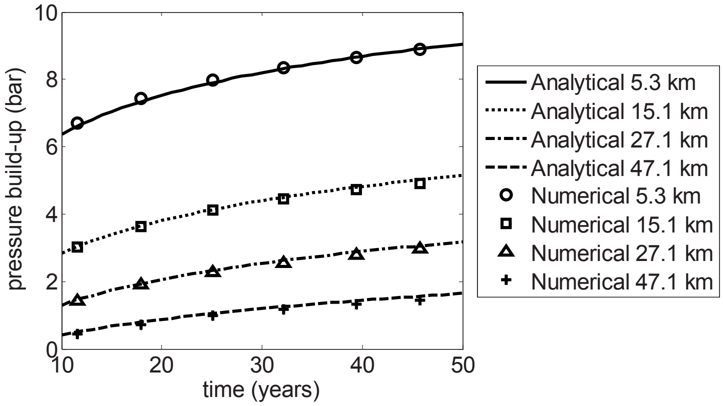

Fig. 4. Comparison of pressure buildup from numerical simulations and the Theis solution for a dipping aquifer (Scenario 1).

4.2. Scenario 1

In this scenario, we have simulated brine injection and examined pressure buildup at different distances from the injection well in the updip direction. The injection rate is 1.0 Mtonne/year. Because there is a depth trend for the properties of the formation material (e.g., porosity and permeability) and the fluid (e.g., salinity and viscosity), we have used average values of the fluid and medium properties between the injection well and pressure observation points for the analytical calculations. From Fig. 4, it is evident that despite the depth trend induced non-homogeneity the simple analytical method can yield results well matching those obtained by numerical simulations.

4.3. Scenario 2

This scenario is based on the site-specific conditions at the Scania site. The considered formation is bounded by three faults and thus constitutes a closed reservoir. The reservoir covers an area of about 2800 km^2. Pressure buildup increases much faster in a closed system than in an open system. Fig. 5 presents the simulated pressure buildup in the reservoir domain at 10 and 50 years. As shown in Fig. 5, the pressure buildup at a distance 3 km away from the injection well reaches about 35 bars and 60 bars for injection of 10 and 50 years, respectively. Comparing this with Scenario 1, one can notice the fast increase of pressure in the system.

Excessive pressure buildup at the faults may lead to risks of fault reactivation. Therefore, it is of interest to study the pressure response at locations close to the faults. Here, we have chosen three points in the reservoir domain close to the three faults (See Fig. 6) for pressure buildup examination. These points represent the closest points on the boundaries to the injection well. Fig. 6 (left) also shows the first image wells of the injection wells with respect to the three boundaries. Note that, here, we have not considered the secondary image wells (i.e., image wells of the image wells).

Numerical simulations (Fig. 6) show that the pressure at the three points (P1, P2 and P3) almost increase linearly during the 50-year injection. This indicates the strong impact of closed boundaries imposed by the faults which are 20-30 km away from the injection well. As a preliminary analysis, the analytical calculations are based on the simple superposition of the pressure buildup by the injection well and the first imaginary wells. Fig. 6 (right) shows that this simple analytical calculation can well match the numerical simulated pressure buildup for early times (< 20 years) but underestimate the pressure buildup for later times.

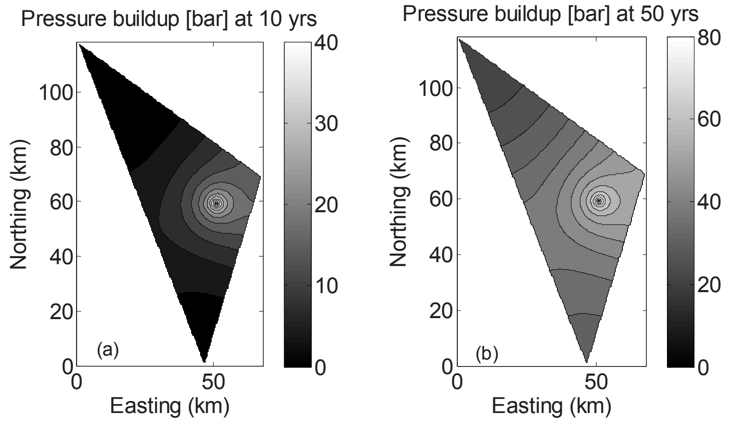

Fig. 5. Spatial distribution of the simulated pressure buildup (bars) for the Scania site at 10 and 50 years.

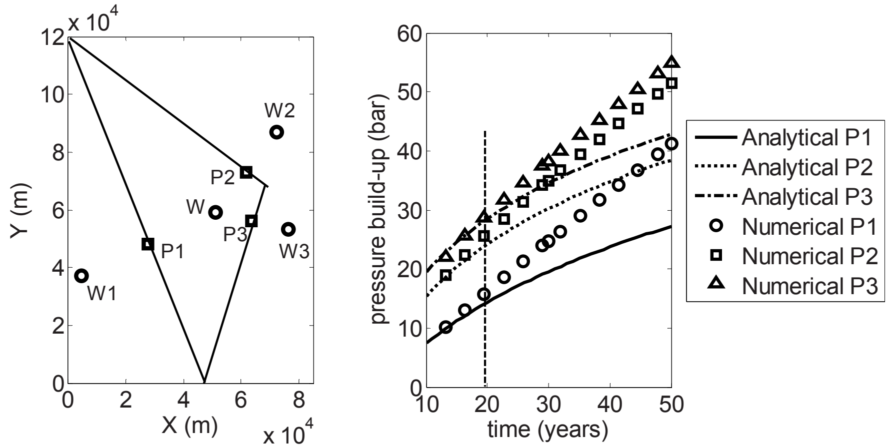

Fig. 6. Left: positions of the injection well (W), primary image wells (W1, W2, W3) and points on the three faults (P1, P2, P3) for examination of pressure buildup. Right: comparison of simulated pressure buildup and the analytical calculations based on the injection well and the first image wells.

5. Summary and Conclusions

Geological storage of CO_2 can cause large-scale pressure buildup and far-field brine migration as well as their associated hydrogeological impacts, which may become a limiting factor for the CO_2 storage capacity. It is therefore necessary to carefully study the evolution and impact of the pressure plume and brine migration. In this study, we have applied both numerical modelling and analytical calculation for the estimation of far-field pressure buildup, considering a generic scenario of dipping aquifer and a site-specific scenario for the Scania site, southwest Sweden. We have examined the effect of depth-dependent fluid and material properties as well as formation geometries on far-field pressure buildup. The use of simple analytical calculations for the estimation of pressure buildup has also been evaluated. The following conclusions are summarized:

(i) Far field pressure buildup can be modeled using single-phase (brine injection) flow simulations. Two-phase flow effect on the pressure perturbation is local (within a few kilometers from the well);

(ii) For a large, dipping aquifer with depth-dependent properties (e.g., φ, k, temperature, brine viscosity, etc), the Theis solution can well approximate the pressure response, using averaged parameters of those between the injection point and the point of interest for analysing pressure buildup;

(iii) A simple analytical calculation method based on the method of images for pressure buildup is evaluated for a storage reservoir (southwest Sweden) bounded by impermeable faults. For early times (<20 years), the analytical calculation using only primary image wells can match the simulated pressure buildup well. For later times, the analytical calculation underestimates the pressure buildup.

In future work, we will refine the analysis of pressure response for the Scania site by considering the angles between straight-line boundaries and their implication on the choice of the number of secondary image wells. We will also analyse the scenario of brine displacement through permeable faults or abandoned wells in order to quantify the brine leakage rate.

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References

[1] Mathias SA, González Martínez de Miguel GJ, Thatcher KE, Zimmerman RW. Pressure buildup during CO_2 injection into a closed brine aquifer. *Transport in Porous Media* 2011;**89**:383–97.

[2] Nicot J-P. Evaluation of large-scale CO2 storage on fresh-water sections of aquifers: An example from the Texas Gulf Coast Basin. *International Journal of Greenhouse Gas Control* 2008;**2**:582–93.

[3] Birkholzer JT, Zhou Q. Basin-scale hydrogeologic impacts of CO2 storage: Capacity and regulatory implications. *International Journal of Greenhouse Gas Control* 2009;**3**:745–56.

[4] Zhou Q, Birkholzer JT, Mehnert E, Lin Y-F, Zhang K. Modeling basin- and plume-scale processes of CO_2 storage for full-scale deployment. *Ground Water* 2010;**48**:494–514.

[5] Person M, Banerjee A, Rupp J, Medina C, Lichtner P, Gable C et al. Assessment of basin-scale hydrologic impacts of CO_2 sequestration, Illinois basin. *International Journal of Greenhouse Gas Control* 2010;**4**:840–54.

[6] Zhou Q, Birkholzer JT, Tsang C-F, Rutqvist J. A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations. *International Journal of Greenhouse Gas Control* 2008;**2**:626–39.

[7] Mathias SA, Hardisty PE, Trudell MR, Zimmerman RW. Approximate solutions for pressure buildup during CO_2 injection in brine aquifers. *Transport in Porous Media* 2009;**79**:265–84.

[8] Mathias SA, Gluyas JG, González Martínez de Miguel GJ, Hosseini SA. Role of partial miscibility on pressure buildup due to constant rate injection of CO2 into closed and open brine aquifers. *Water Resources Research* 2011;**47**:W12525.

[9] Bradshaw J, Bachu S, Bonijoly D, Burruss R, Holloway S, Christensen NP et al. CO2 storage capacity estimation: Issues and development of standards. *International Journal of Greenhouse Gas Control* 2007;**1**:62–8.

[10] Lemieux J-M. Review: The potential impact of underground geological storage of carbon dioxide in deep saline aquifers on shallow groundwater resources. *Hydrogeology Journal* 2011;**19**:757–78.

[11] Pruess K, Oldenburg C, Moridis G. *TOUGH2 User's Guide*, Version 2.0, Report LBNL-43134. Lawrence Berkeley National Laboratory. Berkeley, California; 1999.

[12] Pruess K, Spycher N. ECO2N – A fluid property module for the TOUGH2 code for studies of CO2 storage in saline aquifers. *Energy Conversion and Management* 2007;**48**:1761–7.

[13] Theis, CV. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *Transaction American Geophysical Union* 1935;**2**:519-24.

[14] Hantush MS, Jacob CE. Non-steady radial flow in an infinite leaky aquifer. *Transaction American Geophysical Union* 1955;**36**:95-100.

[15] Neuman SP, Witherspoon PA. Theory of flow in a confined two aquifer system. *Water Resources Research* 1969;**5**:803-16.

[16] Ferris JG, Knowles DB, Brown RH, Stallman RW. *Theory of aquifer tests*, U.S. Geological Survey Water-Supply Paper 1536-E, 1962.

[17] Chasset C, Jarsjö J, Erlström M, Cvetkovic V, Destouni G. Scenario simulations of CO2 injection feasibility, plume migration and storage in a saline aquifer, Scania, Sweden. *International Journal of Greenhouse Gas Control* 2011;**5**:1303–18.

[18] Yang Z, Tian L, Niemi A, Fagerlund F. Upscaling of the constitutive relationships for CO2 migration in multimodal heterogeneous formations. *International Journal of Greenhouse Gas Control*. In Press, doi:10.1016/j.ijggc.2012.11.015.

[19] Erlström M, Silva O, de Vries LM, Shtivelman V, Gendler M, Goldberg I et al. *3D structures of test sites*. EU FP7 MUSTANG Project Report D022. 2010, http://www.co2mustang.eu/MustangDeliverables.aspx.